



UNIVERSITY
OF WOLLONGONG
AUSTRALIA

University of Wollongong
Research Online

Faculty of Law - Papers (Archive)

Faculty of Law, Humanities and the Arts

2009

Does otolith chemistry indicate diadromous lifecycles for five Australian riverine fishes?

Ronald J. West

University of Wollongong, ron@uow.edu.au

N. G. Miles

University of Wollongong, nmiles@uow.edu.au

M. D. Norman

The Australian National University, Marc.Norman@anu.edu.au

Publication Details

Miles, N. G., West, R. J. & Norman, M. D. (2009). Does otolith chemistry indicate diadromous lifecycles for five Australian riverine fishes?. *Marine and Freshwater Research*, 60 904-911. Copyright CSIRO 2009.

Research Online is the open access institutional repository for the University of Wollongong. For further information contact the UOW Library:
research-pubs@uow.edu.au

Does otolith chemistry indicate diadromous lifecycles for five Australian riverine fishes?

Abstract

Diadromy is an important characteristic of the lifecycle of many Australian coastal fishes, but many of these species remain poorly studied. The migratory patterns of five riverine fish species from south-eastern Australia were examined using otolith chemistry. Analyses of individual otoliths from wild-caught fishes revealed distinctive lateral variation in otolith Sr : Ca values that provide good evidence for an amphidromous lifecycle for two species: *Myxus petardi* and *Gobiomorphus australis*. *Gobiomorphus coxii*, *Potamalosa richmondia* and *Notesthes robusta* displayed Sr : Ca patterns that indicated that these species may have more complex movements between marine and fresh water. Overall, these results provided quantitative data that supported the lifecycles previously hypothesised for most of the studied fish species. However, *M. petardi*, which was thought to be catadromous, displayed Sr : Ca variations that suggested an amphidromous lifecycle, at least for the specimens examined. These results also provided further evidence to demonstrate that otolith chemistry is a useful tool for studying the movement patterns of diadromous species and this technique will be especially valuable in identifying species that are most at risk from river regulation and barriers to migration.

Keywords

does, fishes, chemistry, riverine, diadromous, five, lifecycles, otolith, australian, indicate

Disciplines

Law

Publication Details

Miles, N. G., West, R. J. & Norman, M. D. (2009). Does otolith chemistry indicate diadromous lifecycles for five Australian riverine fishes?. *Marine and Freshwater Research*, 60 904-911. Copyright CSIRO 2009.

Does otolith chemistry indicate diadromous lifecycles for five Australian riverine fishes?

N. G. Miles^{A,C,D}, R. J. West^A and M. D. Norman^B

^ASchool of Biological Sciences, University of Wollongong, NSW, 2522, Australia.

^BResearch School of Earth Sciences, Australian National University, Canberra, ACT, 0200, Australia.

^CPresent address: Field Science Centre, Hokkaido University, Sapporo 060-0809, Japan.

^DCorresponding author. Email: nmiles10@hotmail.com

Abstract. Diadromy is an important characteristic of the lifecycle of many Australian coastal fishes, but many of these species remain poorly studied. The migratory patterns of five riverine fish species from south-eastern Australia were examined using otolith chemistry. Analyses of individual otoliths from wild-caught fishes revealed distinctive lateral variation in otolith Sr:Ca values that provide good evidence for an amphidromous lifecycle for two species: *Myxus petardi* and *Gobiomorphus australis*. *Gobiomorphus coxii*, *Potamalosa richmondia* and *Notesthes robusta* displayed Sr:Ca patterns that indicated that these species may have more complex movements between marine and fresh water. Overall, these results provided quantitative data that supported the lifecycles previously hypothesised for most of the studied fish species. However, *M. petardi*, which was thought to be catadromous, displayed Sr:Ca variations that suggested an amphidromous lifecycle, at least for the specimens examined. These results also provided further evidence to demonstrate that otolith chemistry is a useful tool for studying the movement patterns of diadromous species and this technique will be especially valuable in identifying species that are most at risk from river regulation and barriers to migration.

Additional keywords: amphidromy, barium, catadromy, ICPMS, migration, strontium.

Introduction

Migration is an important characteristic of the lifecycle of many marine and freshwater fishes (Harden Jones 1968). However, migrations have large biological and physiological costs and place fish at a heightened risk from anthropogenic impacts (Gross *et al.* 1988; McDowall 1988; Jonsson *et al.* 1999). Possibly one of the most threatened groups of migratory fishes are those that display diadromy, that is, fishes that migrate between marine and freshwater habitats to complete their lifecycle (Angermeier 1995; Jonsson *et al.* 1999; McDowall 1999). For example, coastal riverine fishes of south-eastern (SE) Australia inhabit an area of rapidly increasing development and population growth that results in several threats to the survival of fish in this region (Harris 1984; Faragher and Harris 1994). However, with limited information available on the lifecycle requirements of many of these fish species, assessing impacts of threats can be difficult (Harris 1984).

Future management and conservation of these migratory fishes, particularly diadromous fishes, needs to be based on a thorough understanding of their lifecycles (Jonsson *et al.* 1999; McDowall 1999). However, the lifecycles and migrations of diadromous fishes can be difficult to study because many species display sedentary and secretive behaviour, and may also move in small groups, during high flows or under the cover of darkness (McDowall 1988; Keith 2003; Jowett *et al.* 2005). Several species also have migrating larval or juvenile stages that can be

difficult to detect or study in the wild owing to their small size and often unpigmented transparent bodies (McDowall 1988; Closs *et al.* 2003; Keith 2003; Pusey *et al.* 2004). Therefore, many diadromous species have lifecycles that are not easily investigated using traditional survey techniques, telemetry or fish counters.

Recent advances in analytical techniques have enabled the detection of fine-scale variations in the trace elements of fish otoliths, and have provided a new source of information on the migratory history of fishes (Elfman *et al.* 2000; Milton *et al.* 2000; Gillanders 2005). Otoliths are formed from calcium carbonate or aragonite (CaCO₃) that is laid in concentric rings around a central core as fish grow and is deposited at ~1–5 µm per day along the main growth axis (Markwitz *et al.* 2000). The examination of fish movements between marine and freshwaters has been possible by measuring the concentrations of strontium (Sr) in the otolith, because this element is found in higher concentrations in sea water than in fresh water (Kalish 1990; Secor and Rooker 2000; Crook *et al.* 2006). As a result, otolith layers formed in marine waters typically exhibit higher ratios of Sr:Ca than layers formed in fresh water (Milton *et al.* 2000; Crook *et al.* 2006).

However, interpretation of movement patterns using otolith chemistry relies on a strong relationship between the ambient water and otolith concentrations, and otolith chemistry can be affected by factors other than salinity, such as species, age,

temperature, food and behaviour (Kalish 1990; Radtke and Shafer 1992; Secor and Rooker 2000; Buckel *et al.* 2004). In addition, some estuarine and fresh waters can have elevated levels of Sr (Kraus and Secor 2004; Crook *et al.* 2006; Limburg and Siegel 2006). As a result, barium (Ba), an element typically more available for incorporation into otoliths in fresh water compared with sea water has also been used in otolith chemistry studies (Elsdon and Gillanders 2005a, 2006; Hamer *et al.* 2006; Hale and Swearer 2008). Therefore, the combination of these two elements (Sr and Ba) should provide a more accurate indication of the historical record of fish movement between marine and freshwater environments (Bath *et al.* 2000; Elsdon and Gillanders 2005b; Crook *et al.* 2006). In the present study, otolith Sr : Ca and Ba : Ca for five riverine fish species from SE Australia were analysed to determine whether the movements patterns are consistent with the diadromous lifecycles that have previously been suggested for these species (Table 1).

Materials and methods

Fish collection and study area

Wild *Potamalosa richmondia*, *Myxus petardi*, *Notesthes robusta*, *Gobiomorphus australis* and *Gobiomorphus coxii* were collected from five catchments of SE Australia between May 2004 and April 2006 during *ad hoc* netting surveys (Fig. 1, Table 2). The Hunter (catchment size 22 000 km²), Shoalhaven (7500 km²) and Clyde Rivers (2900 km²) are medium to large catchments in SE Australia. These rivers originate in deep gorges and valleys that open up into wide valleys bordered by alluvial terraces or floodplains as they approach the coast (Sussmilch 1914; Roy *et al.* 2001). Macquarie Rivulet (217 km²) and Hewitts Creek (16 km²) drain from the Illawarra escarpment and both have entrances that are intermittently closed to the sea. After capture, fish were immediately euthanased in an ice water slurry mix, after which the majority of specimens were frozen. Some smaller specimens were stored in ethanol before later processing.

Otolith removal and preparation

Sagittal otoliths were removed from the fish, cleaned, rinsed and allowed to dry on glass slides before being stored in micro-centrifuge tubes for later preparation. All sample cleaning and diluting was done using ultra-pure water. Plasticware and glassware were washed in 10% HNO₃ and rinsed several times in water before use. The otoliths were embedded in epoxy resin (EpoFix, Struers, Denmark) and sectioned transversely through the centre using a low-speed Isomet diamond saw (Buehler, Lake Bluff, IL, USA) lubricated with water (Elsdon and Gillanders 2002; Crook *et al.* 2006). Sections of ~400 µm were then polished using 9-µm lapping film until they were ~300 µm thick. These sections were rinsed in ultra-pure water and dried on glass slides. Prepared sections were mounted on glass slides in groups of up to eight per slide with additional epoxy resin. Mounted sections were then sonicated for 5 min, rinsed and dried in a laminar-flow cabinet before being stored in clean sealable plastic bags until microchemical analyses.

Microchemical analyses

Laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) was used to determine elemental concentrations

Table 1. Selected riverine fish species from south-eastern Australia and their previously suggested lifecycles

Also shown are the minimum sizes for mature adults

| Common name | Species name | Authority | Lifecycle | Adult length (mm) | Reference |
|--------------------|-------------------------------|-----------------|---------------------------|-------------------|---|
| Freshwater herring | <i>Potamalosa richmondia</i> | Macleay, 1879 | Catadromous | 100 | (Pidgeon 1989; Briggs and McDowall 1996) |
| Bullrout | <i>Notesthes robusta</i> | Günther, 1860 | Freshwater/catadromous | 75 | (Pollard and Parker 1996; Pusey <i>et al.</i> 2004) |
| Freshwater mullet | <i>Myxus petardi</i> | Castelnau, 1875 | Catadromous | 300 | (Thomson 1996) |
| Stripe gudgeon | <i>Gobiomorphus australis</i> | Krefft, 1864 | Amphidromous | 70 | (Pusey <i>et al.</i> 2004) |
| Cox's gudgeon | <i>Gobiomorphus coxii</i> | Krefft, 1864 | Amphidromous ^A | 70 | (Pusey <i>et al.</i> 2004) |

^A Possibly a marginally diadromous species.

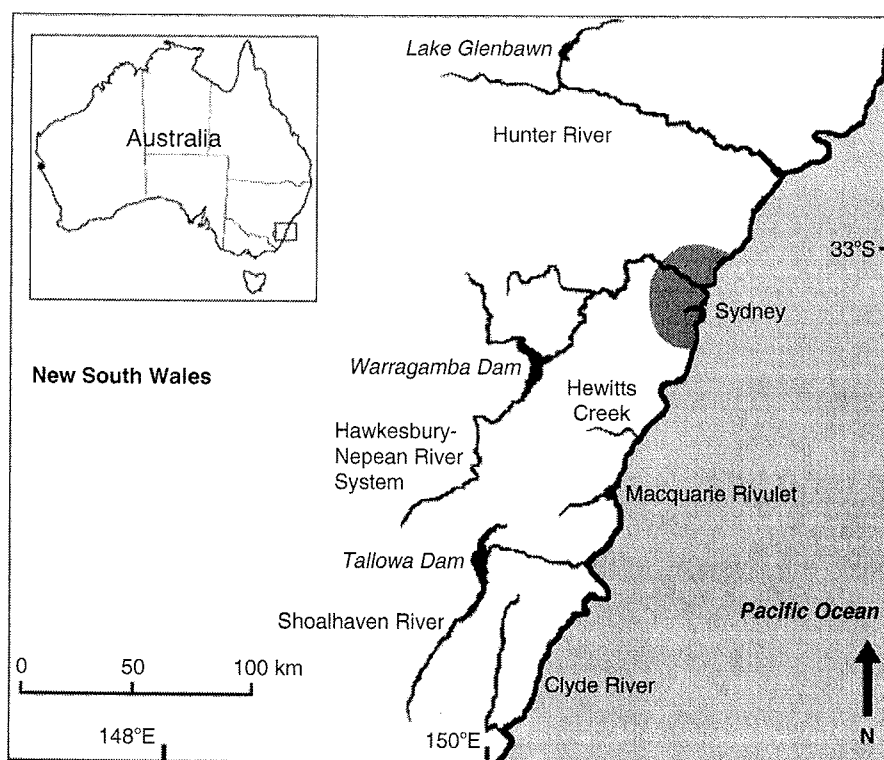


Fig. 1. Map showing sampling locations in south-eastern Australia.

Table 2. Summary information for fish used in the present study including: length range (L_T), salinity range at collection locations, collection location and collection rivers

F/S = freshwater–saltwater interface, L = lowland or middle reaches at altitudes <40 m and S = slopes or upper reaches at altitudes >40 m

| Species | No. | L_T (mm) | Collection salinity | Collection location | Collection rivers |
|----------------------|-----|------------|---------------------|---------------------|---------------------------------------|
| <i>P. richmondia</i> | 15 | 162–274 | 0.04–0.69 | F/S, L, S | Hunter, Shoalhaven, Clyde |
| <i>N. robusta</i> | 7 | 34–131 | 0.09–1.63 | F/S, L | Shoalhaven, Clyde |
| <i>M. petardi</i> | 17 | 86–468 | 0.08–0.09 | L, S | Shoalhaven, Clyde |
| <i>G. australis</i> | 10 | 53–130 | 0.08–0.69 | F/S, L, S | Shoalhaven, Clyde, Macquarie, Hewitts |
| <i>G. coxii</i> | 3 | 103–144 | 0.08–0.69 | F/S, L | Shoalhaven, Clyde |

of the otoliths. Analytical equipment consisted of an ArF ultraviolet excimer laser ($\lambda = 193$ nm) coupled to an Agilent 7500 quadrupole ICPMS (Yokogawa Analytical System, Kyoto, Japan) (Eggins *et al.* 1998). The instrument measures several masses sequentially; ^{43}Ca , ^{88}Sr and ^{138}Ba were chosen for the present study. Laser ablation of the samples was conducted using a 10-Hz pulse rate and a 32- μm diameter spot under helium and hydrogen, and the ablated material was mixed with argon carrier gas before introduction into the ICPMS. The sample cell holds a 50-mm glass microscope slide on which we had mounted up to eight otoliths. Reference standards (National Institute of Standards and Technology, NIST 612 glass) were measured regularly to calibrate the relative sensitivity of each analyte mass (Norman *et al.* 1996; Elsdon and Gillanders 2002, 2004; Crook *et al.* 2006). The standard was measured each time the sealed sample stage was opened and again after every four otoliths (mid way through each sample set). Gas background readings measured on the sample carrier gas without ablation were measured

for 15 s before each analysis and subtracted from the measured intensity of each analyte mass. A continuous scan was undertaken across the otoliths from one edge to the other, passing through the core using an automated stage at a scan rate of ~ 0.3 mm per minute. Each analysis was normalised to the CaO content expected for pure calcite (55 wt% CaO) or measured previously in the NIST 612 glass (Norman *et al.* 1996) to correct for variations in ablation yield from the sample relative to the glass standard and convert the measured ion intensities to absolute concentrations in ppm. Details of these calculations are given in Norman *et al.* (1996). Elemental concentrations were normalised to ^{43}Ca and data were presented as concentration ratios in units of mmol mol^{-1} (Sr : Ca) and $\mu\text{mol mol}^{-1}$ (Ba : Ca).

Movements between fresh and salt water were inferred from the patterns in Sr : Ca and Ba : Ca from the full otolith scans. Interpretation of this data was aided through a preliminary experiment that examined the uptake of Sr and Ba into otoliths of the study species under aquaria conditions (Miles 2007). The inner

regions of the otoliths, relating to larval and juvenile growth, as well as the outer regions relating to subadult and adult growth were then compared. To smooth the data points, Sr:Ca and Ba:Ca values were averaged for 5- μ m increments of otolith material.

Statistical analyses

To further investigate the lifecycle of *M. petardi*, mean Sr:Ca and Ba:Ca values in the central region of the otolith relating to larval and juvenile growth were compared with those on the outer region of the otolith (which corresponds to adult growth) across all specimens using Student *t*-tests. All statistical analyses were undertaken in SPSS ver. 10.0 (SPSS Inc, Chicago, IL, USA).

Results

Otolith chemistry of wild-caught fish

Otolith Sr:Ca transects for *P. richmondia* typically showed a series of peaks from the otolith core towards the edge (Fig. 2a, b). Ba:Ca showed variable patterns, with a series of high and low values that were mostly unrelated to Sr:Ca values. However, in some otoliths, the Ba:Ca values declined with the first peak in Sr:Ca (Fig. 2a, b). The highly variable values for both ratios and the consistent peaks and troughs of Sr:Ca for all fish across all catchments suggested that the *P. richmondia* examined in this study had inhabited waters with a variety of salinities.

Otolith Sr:Ca in the inner regions of *M. petardi* otoliths were considerably higher than those in the outer region (Fig. 2c, d). The high Sr:Ca values towards the core were mirrored by lower Ba:Ca values in this region of the otolith. The mean Sr:Ca values from the inner region of *M. petardi* otoliths across all fish from all catchments were significantly higher than those from the outer region (*t*-test, $t_{2541} = 98.6$, $P < 0.001$, Fig. 3). Ba:Ca displayed the opposite trends, where significantly lower levels were found in the central region ($t_{3117} = 123.8$, $P < 0.001$, Fig. 3). In addition, *M. petardi* juveniles <150 mm showed elevated Sr:Ca and lowered Ba:Ca levels across most of the otolith, which may suggest that these fish had only recently entered fresh water (Fig. 2e). Overall, the consistent peaks of Sr:Ca values in the region of the otolith relating to larval/juvenile growth and the lower values during adult growth suggest that early life is spent in higher salinity waters and the remainder of life is spent in fresh water. These patterns suggest that *M. petardi* examined in the present study displayed an amphidromous lifecycle.

The transects for Sr:Ca values in *N. robusta* otoliths showed a highly variable pattern, with several peaks and troughs from the inner region of the otolith to the edge (Fig. 2f, g). The transects for Ba:Ca values were also highly variable between otoliths and few discernible patterns were observed (Fig. 2f, g). Further, there appeared to be no consistent pattern in otolith chemistry as a result of the collection river. The highly variable values of Sr:Ca alone would seem to suggest that the specimens examined in this study had inhabited waters with a variety of salinities.

Otolith Sr:Ca transects for *G. australis* typically showed elevated levels in the central region and lowered levels on the outer region. The first peak was situated in the middle of the central region and the second occurred after a short band of lower Sr:Ca values (Fig. 2h, i). Patterns were consistent for all fish from all catchments. For example, the transects for *G. australis*

are fish from Hewitts Creek (Fig. 2h) and the Shoalhaven River (Fig. 2i). The lower ratios in the central region may indicate a period of freshwater residency (or downstream drift) before entering saline waters. These values were mirrored by Ba:Ca values and together strongly suggest that early stages of the lifecycle are spent in waters with elevated salinities. These patterns are consistent with amphidromy. The transects for Sr:Ca values in the limited number of *G. coxii* otoliths examined in this study displayed similar patterns to *G. australis*; however, the levels of Sr:Ca relating to larval/juvenile were proportionally much smaller than the corresponding levels in *G. australis* (Fig. 2j). These results suggest that some portion of the early life might be spent in waters with elevated salinities.

Discussion

The results from this research provide new data on the movement patterns of five fish species from SE Australia. In general, the Sr:Ca values determined using LA-ICPMS demonstrated differences within the otoliths of all species examined and indicated that all of these species probably exhibit residency in both marine and freshwater environments at some stage of their lifecycle (Table 3). Many of these patterns could be consistent with patterns of diadromy reported elsewhere (David *et al.* 2004; McCulloch *et al.* 2005; Crook *et al.* 2006, 2008).

The correlation between Sr:Ca and Ba:Ca was often poor in the outer region of the otolith, which made interpreting movements difficult for some species (i.e. *P. richmondia* and *N. robusta*). Similar results have been reported elsewhere for diadromous fish, where Ba:Ca has been difficult to interpret or relate to ambient salinity (Crook *et al.* 2006; Hale and Swearer 2008). Crook *et al.* (2006) also reported difficulties in interpreting the outer edges of otolith from Australian grayling *Prototroctes maraena* (Günther, 1864) and they suggested that this may have been the result of movement into estuaries or between tributaries. The present study did not examine the water chemistry of the collection rivers; however, the relationships between Sr and Ba and salinity in river waters have been quantified in other SE Australian streams (Crook *et al.* 2006, 2008). Despite some high Sr concentrations in ambient fresh waters, which were also reflected in the otolith chemistry, the otolith Sr:Ca patterns that demonstrate diadromy remained consistent (Crook *et al.* 2006). It was also found that otolith chemistry patterns suggesting diadromy were consistent across all catchments for the species examined.

The apparent movements between fresh water and salt water found in this study for *P. richmondia* might support previous reports of catadromy for this species (Merrick and Schmida 1984; Koehn and O'Connor 1990; Briggs and McDowall 1996). Pidgeon (1989) suggested that the lifecycle of this species involved adult fish undertaking annual winter downstream migrations from freshwater to marine areas to spawn. Juveniles are then thought to migrate back upstream after a period of development in marine environments (Pidgeon 1989). After spending the winter in marine waters, *P. richmondia* adults also migrate back upstream. The series of peaks and troughs in otolith Sr:Ca values (Fig. 2a, b), the number of which fits within the known longevity of this species and the likely age of the specimens (Pidgeon 1989), supports the hypothesis of an annual migration of

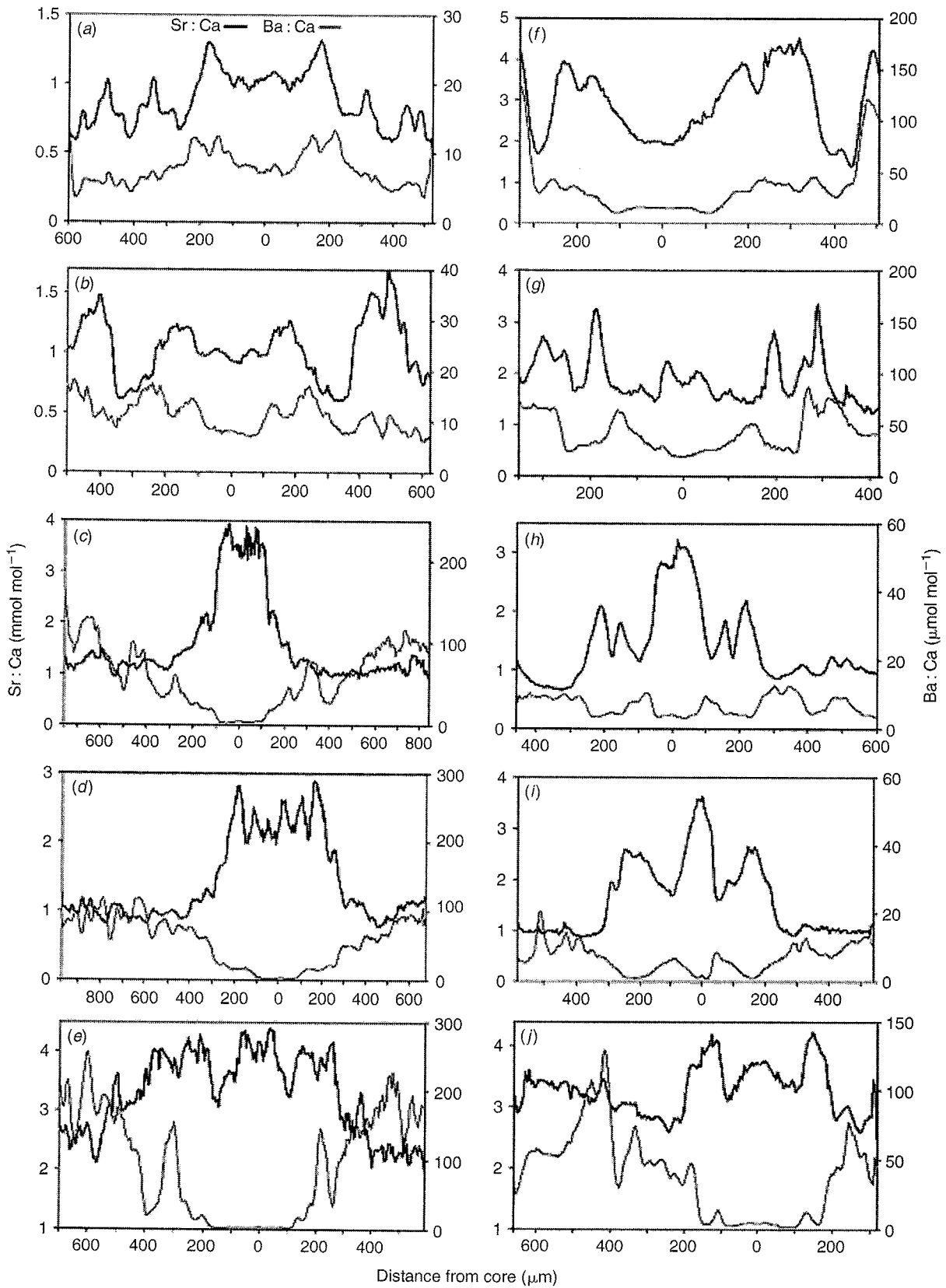


Fig. 2. Sr:Ca (mmol mol⁻¹) and Ba:Ca (μmol mol⁻¹) values along transects across otoliths of representative subsets of *P. richmondia* (a, b), *M. petardi* (c, d, e), *N. robusta* (f, g), *G. australis* (h, i) and *G. coxii* (j). (e) and (f) represent the data for juvenile fish. Scales for both axes vary for each fish.

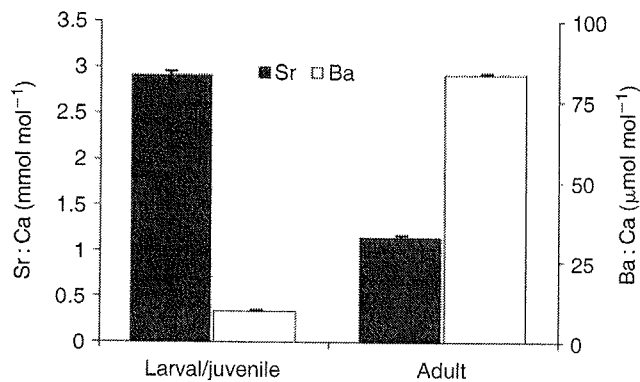


Fig. 3. Mean (+s.e.) Sr:Ca and Ba:Ca values from *M. petardi* otoliths across all fish from all catchments, comparing larval/juvenile and adult growth.

P. richmondia between marine and fresh water. However, interpreting migratory patterns of catadromous or euryhaline species such as *P. richmondia* from otolith chemistry may be difficult because the downstream migration into marine waters occurs during the winter months. This means that potentially less otolith material is deposited and fine-scale variations may be difficult to detect (Radtko and Shafer 1992; Secor and Rooker 2000; Elsdon and Gillanders 2002). Many fish movements also coincide with flood events and it is recommended that future studies should consider examining the water chemistry over long time frames in several flow conditions.

The apparent multiple movements by *N. robusta* between fresh water and salt water is contradictory to some previous reports that suggested the life cycle is completed in fresh water (Pollard and Parker 1996). The results from the present study are consistent with catadromy, which was also suggested by Pusey *et al.* (2004) after they collected gravid females and small juveniles from estuarine areas. As a result, it seems unlikely that this is an exclusively freshwater species, but if the records of juveniles occurring above barriers prove to be correct, it is possible that landlocked populations (i.e. where diadromy is abandoned for an exclusively freshwater lifecycle) could exist or that diadromy is facultative.

Otolith chemistry for *G. australis* and *G. coxii* displayed Sr:Ca and Ba:Ca patterns that support their previously suggested amphidromous and marginally amphidromous lifecycles (Koehn and O'Connor 1990; Larson and Hoese 1996; Pusey *et al.* 2004). This includes a marine larval stage in *G. australis* followed by upstream migrations by juveniles into freshwater habitats where the remainder of their lifecycle is completed (Koehn and O'Connor 1990; Larson and Hoese 1996; Pusey *et al.* 2004). *G. australis* juveniles have been collected in estuarine areas and small fish observed recruiting back into freshwaters in spring (Larson and Hoese 1996; Pusey *et al.* 2004; Miles 2007). The present study also indicated that juveniles of *G. coxii* recruit from brackish or estuarine water into fresh water (Koehn and O'Connor 1990; Larson and Hoese 1996; Pusey *et al.* 2004). The reduced amplitude in Sr:Ca peaks for *G. coxii* compared with those observed for the closely related *G. australis* may reflect recruitment from waters with lower salinities. This

Table 3. Summary of lifecycle type previously suggested for the five study species, and the suggested lifecycle type resulting from the present study

| Species | Lifecycle type | |
|----------------------|---------------------------|---------------------------|
| | Current | Previous |
| <i>P. richmondia</i> | Catadromous/euryhaline | Catadromous |
| <i>M. petardi</i> | Amphidromous | Catadromous |
| <i>N. robusta</i> | Catadromous/euryhaline | Freshwater/catadromous |
| <i>G. australis</i> | Amphidromous | Amphidromous |
| <i>G. coxii</i> | Amphidromous ^A | Amphidromous ^A |

^APossibly a marginally diadromous species.

would suggest that this species could be 'marginally' amphidromous. Further research is required to determine the significance of these differences in Sr:Ca between these two species. The lower Sr:Ca values found between the peaks around the otolith core in these species might reflect the downstream larval drift period in fresh water before they enter the marine environment (Fig. 2*h, i, j*). Landlocking has been observed for the related common bully, *Gobiomorphus cotidianus* (McDowall, 1975), in New Zealand (Closs *et al.* 2003); however, no evidence of landlocking was recorded in the populations of *Gobiomorphus* examined in this study. Diadromy is further supported because there are no records of *G. australis* and *G. coxii* forming landlocked populations, despite the large number of barriers in coastal catchments in the range of these species (Harris 1984).

Otolith chemistry for *M. petardi* (Fig. 2) strongly suggested an amphidromous lifecycle, rather than the previously assumed catadromous lifecycle. There appears to be very little published data supporting catadromy in this species. The main evidence for a catadromous lifecycle emanates from Humphrey (1979), where ripe fish were recorded in brackish water after flood events in the Macleay River. As a result, spawning was thought to occur in waters with salinities of 5 to 15. This hypothesis is not supported by the present study, which indicates that after a period in marine waters as juveniles, the remainder of life is spent in fresh water. The fish recorded by Humphrey (1979) in brackish water could reflect downstream displacement during a flood event, and not active migration. In addition, ripe and spent fish were collected in fresh water during a recent study (Miles 2007) and the otolith chemistry of the spent fish displayed no sign of recent movement into salt water (see Fig. 2*d*). The apparent lack of adults from surveys in several estuarine studies (e.g. West and Walford 2000) could further support that there is no active downstream migration of adults to marine areas for spawning.

Before this study, very little data existed on the lifecycle and movement patterns of these five riverine species. Otolith chemistry has proven to be a useful tool in providing new data for these species. The movement patterns indicated by otolith chemistry in the present study highlight the need to maintain and improve the connectivity in riverine environments. This is especially important in eastern Australia because there are over 290 dams and weirs in coastal streams between southern Queensland and northern Victoria that form major barriers to fish migration (Harris 1984). Given the widespread regulation of rivers in many regions of the world, it is important that the lifecycles of migratory fishes

are better understood. Otolith chemistry is likely to play a key role in providing this new information.

Acknowledgements

This work was funded by an Australian Postgraduate Award to NGM and a Science and Innovation Award from the Bureau of Rural Sciences and Fisheries Research and Development Corporation. Julian Hughes (NSW DPI) is thanked for his assistance with otolith preparations. Tony Miskiewicz, Travis Elsdon and anonymous referees are thanked for their comments on earlier versions of this manuscript. All experiments were undertaken in accordance with the University of Wollongong's Animal Ethics Committee (Protocol AE06-17).

References

- Angermeier, P. L. (1995). Ecological attributes of extinction-prone species – loss of fresh-water fishes of Virginia. *Conservation Biology* **9**, 143–158. doi:10.1046/J.1523-1739.1995.09010143.X
- Bath, G. E., Thorrold, S. R., Jones, C. M., Campana, S. E., McLaren, J. W., et al. (2000). Strontium and barium uptake in aragonitic otoliths of marine fish. *Geochimica et Cosmochimica Acta* **64**, 1705–1714. doi:10.1016/S0016-7037(99)00419-6
- Briggs, I. C., and McDowall, R. M. (1996). Family Clupeidae: herrings. In 'Freshwater Fishes of South-eastern Australia'. (Ed. R. M. McDowall.) pp. 44–47. (Reed: Sydney.)
- Buckel, J. A., Sharack, B. L., and Zdanowicz, V. S. (2004). Effect of diet on otolith composition in *Pomatomus saltatrix*, an estuarine piscivore. *Journal of Fish Biology* **64**, 1469–1484. doi:10.1111/J.0022-1112.2004.00393.X
- Closs, G. P., Smith, M., Barry, B., and Markwitz, A. (2003). Non-diadromous recruitment in coastal populations of common bully (*Gobiomorphus cotidianus*). *New Zealand Journal of Marine and Freshwater Research* **37**, 301–313.
- Crook, D. A., Macdonald, J. I., O'Connor, J. P., and Barry, B. (2006). Use of otolith chemistry to examine patterns of diadromy in the threatened Australian grayling *Prototroctes maraena*. *Journal of Fish Biology* **69**, 1330–1344. doi:10.1111/J.1095-8649.2006.01191.X
- Crook, D. A., Macdonald, J. I., and Raadik, T. A. (2008). Evidence of diadromous movements in a coastal population of southern smelts (*Retropinna*) from Victoria, Australia. *Marine and Freshwater Research* **59**, 638–646. doi:10.1071/MF07238
- David, B., Chadderton, L., Closs, G., Barry, B., and Markwitz, A. (2004). Evidence of flexible recruitment strategies in coastal populations of giant kokopu (*Galaxias argenteus*). DOC Science Internal Series 160. New Zealand Department of Conservation, Wellington.
- Eggs, S. M., Kinsley, L. P. J., and Shelley, J. M. G. (1998). Deposition and element fractionation processes during atmospheric pressure laser sampling for analysis by ICP-MS. *Applied Surface Science* **127–129**, 278–286. doi:10.1016/S0169-4332(97)00643-0
- Elfman, M., Limburg, K. E., Kristiansson, P., Svedang, H., Westin, L., et al. (2000). Complex life histories of fishes revealed through natural information storage devices: case studies of diadromous events as recorded by otoliths. *Nuclear Instruments & Methods in Physics Research. Section B, Beam Interactions with Materials and Atoms* **161–163**, 877–881. doi:10.1016/S0168-583X(99)00923-4
- Elsdon, T. S., and Gillanders, B. M. (2002). Interactive effects of temperature and salinity on otolith chemistry: challenges for determining environmental histories of fish. *Canadian Journal of Fisheries and Aquatic Sciences* **59**, 1796–1808. doi:10.1139/F02-154
- Elsdon, T. S., and Gillanders, B. M. (2004). Fish otolith chemistry influenced by exposure to multiple environmental variables. *Journal of Experimental Marine Biology and Ecology* **313**, 269–284. doi:10.1016/J.JEMBE.2004.08.010
- Elsdon, T. S., and Gillanders, B. M. (2005a). Alternative life-history patterns of estuarine fish: barium elucidates freshwater residency. *Canadian Journal of Fisheries and Aquatic Sciences* **62**, 1143–1152. doi:10.1139/F05-029
- Elsdon, T. S., and Gillanders, B. M. (2005b). Consistency of patterns between laboratory experiments and field collected fish in otolith chemistry: an example and applications for salinity reconstructions. *Marine and Freshwater Research* **56**, 609–617. doi:10.1071/MF04146
- Elsdon, T. S., and Gillanders, B. M. (2006). Temporal variability in strontium, calcium, barium, and manganese in estuaries: Implications for reconstructing environmental histories of fish from chemicals in calcified structures. *Estuarine, Coastal and Shelf Science* **66**, 147–156. doi:10.1016/J.ECSS.2005.08.004
- Faragher, R. A., and Harris, J. H. (1994). The historical and current status of freshwater fish in New South Wales. *Australian Zoologist* **29**, 166–176.
- Gillanders, B. M. (2005). Otolith chemistry to determine movements of diadromous and freshwater fish. *Aquatic Living Resources* **18**, 291–300. doi:10.1051/ALR:2005033
- Gross, M. R., Coleman, R. M., and McDowall, R. M. (1988). Aquatic productivity and the evolution of diadromous fish migration. *Science* **239**, 1291–1293. doi:10.1126/SCIENCE.239.4845.1291
- Hale, R., and Swearer, S. E. (2008). Otolith microstructural and micro-chemical changes associated with settlement in the diadromous fish *Galaxias maculatus*. *Marine Ecology Progress Series* **354**, 229–234. doi:10.3354/MEPS07251
- Hamer, P. A., Jenkins, G. P., and Coutin, P. (2006). Barium variation in *Pagrus auratus* (Sparidae) otoliths: a potential indicator of migration between an embayment and ocean waters in south-eastern Australia. *Estuarine, Coastal and Shelf Science* **68**, 686–702. doi:10.1016/J.ECSS.2006.03.017
- Harden Jones, F. R. (1968). 'Fish Migration.' (Edward Arnold: London.)
- Harris, J. H. (1984). Impoundment of coastal drainages of south-eastern Australia, and a review of its relevance to fish migrations. *Australian Zoologist* **21**, 235–250.
- Humphrey, C. L. (1979). Growth and reproduction of the freshwater or pink-eye mullet, *Trachystoma petardi* (Castelnau), in the Macleay River, N.S.W. Honours Thesis, University of New England, Armidale, Australia.
- Jonsson, B., Waples, R. S., and Friedland, K. D. (1999). Extinction considerations for diadromous fishes. *ICES Journal of Marine Science* **56**, 405–409. doi:10.1006/JMSC.1999.0483
- Jowett, I. G., Richardson, J., and Bonnett, M. L. (2005). Relationship between flow regime and fish abundances in a gravel-bed river, New Zealand. *Journal of Fish Biology* **66**, 1419–1436. doi:10.1111/J.0022-1112.2005.00693.X
- Kalish, J. M. (1990). Use of otolith microchemistry to distinguish the progeny of sympatric anadromous and non-anadromous salmonids. *Fishery Bulletin* **88**, 657–666.
- Keith, P. (2003). Biology and ecology of amphidromous Gobiidae of the Indo-Pacific and the Caribbean regions. *Journal of Fish Biology* **63**, 831–847. doi:10.1046/J.1095-8649.2003.00197.X
- Koehn, J. D., and O'Connor, W. G. (1990). Biological information for management of native freshwater fish in Victoria. Department of Conservation and Environment Freshwater Fish Management Branch. Arthur Rylah Institute for Environmental Research, Melbourne, Victoria.
- Kraus, T., and Secor, D. H. (2004). Incorporation of strontium into otoliths of estuarine fish. *Journal of Experimental Marine Biology and Ecology* **302**, 85–106. doi:10.1016/J.JEMBE.2003.10.004
- Larson, H. K., and Hoes, D. F. (1996). Family Gobiidae, subfamilies Eleotridinae and Butinae: gudgeons. In 'Freshwater Fishes of South-eastern Australia'. (Ed. R. M. McDowall.) pp. 200–219. (Reed Books: Sydney.)
- Limburg, K. E., and Siegel, D. I. (2006). The hydrogeochemistry of connected waterways: the potential of linking geology to fish migrations. *Northeastern Geology and Environmental Sciences* **28**, 254–265.
- Markwitz, A., Grambole, D., Herrmann, F., Trompeter, W. J., Dioses, T., et al. (2000). Reliable micro-measurement of strontium is the key to cracking

- the life-history code in the fish otolith. *Nuclear Instruments & Methods in Physics Research. Section B, Beam Interactions with Materials and Atoms* **168**, 109–116. doi:10.1016/S0168-583X(99)00631-X
- McCulloch, M., Cappo, M., Aumend, J., and Müller, W. (2005). Tracing the life history of individual barramundi using laser ablation MC-ICP-MS Sr-isotopic and Sr/Ba ratios in otoliths. *Marine and Freshwater Research* **56**, 637–644. doi:10.1071/MF04184
- McDowall, R. M. (1988). 'Diadromy in Fishes: Migrations Between Freshwater and Marine Environments.' (Croom Helm: London.)
- McDowall, R. M. (1999). Different kinds of diadromy: different kinds of conservation problems. *ICES Journal of Marine Science* **56**, 410–413. doi:10.1006/JMSC.1999.0450
- Merrick, J. R., and Schmida, G. E. (1984). 'Australian Freshwater Fishes: Biology and Management.' (Griffin Press Ltd: Netley, SA.)
- Miles, N. G. (2007). The biology and ecology of diadromous fish of south eastern Australia. Ph.D. Thesis, University of Wollongong.
- Milton, D. A., Tenakanai, C. D., and Chenery, S. R. (2000). Can the movements of barramundi in the Fly River region, Papua New Guinea be traced in their otoliths. *Estuarine, Coastal and Shelf Science* **50**, 855–868. doi:10.1006/ECSS.2000.0608
- Norman, M. D., Pearson, N. J., Sharma, A., and Griffin, W. L. (1996). Quantitative analysis of trace elements in geological materials by laser ablation ICPMS: Instrumental operating conditions and calibration values of NIST glasses. *Geostandards Newsletter* **20**, 247–261. doi:10.1111/J.1751-908X.1996.TB00186.X
- Pidgeon, R. W. J. (1989). Age and growth of freshwater herring, *Potamalosa richmondia* Macleay (Clupeidae: Hyperlophinae), in the Bellinger River, New South Wales. *Australian Journal of Marine and Freshwater Research* **40**, 679–692. doi:10.1071/MF9890679
- Pollard, D. A., and Parker, P. (1996). Family Scorpaenidae: scorpionfishes. In 'Freshwater Fishes of South-eastern Australia'. (Ed. R. M. McDowall.) pp. 144–145. (Reed: Sydney.)
- Pusey, B. J., Kennard, M. J., and Arthington, A. H. (2004). 'Freshwater Fishes of North-eastern Australia.' (CSIRO Publishing: Melbourne.)
- Radtke, R. L., and Shafer, D. J. (1992). Environmental sensitivity of fish otolith microchemistry. *Australian Journal of Marine and Freshwater Research* **43**, 935–951. doi:10.1071/MF920935
- Roy, P. S., Williams, R. J., Jones, A. R., Yassini, I., Gibbs, P. J., *et al.* (2001). Structure and function of south-east Australian estuaries. *Estuarine, Coastal and Shelf Science* **53**, 351–384. doi:10.1006/ECSS.2001.0796
- Secor, D., and Rooker, J. R. (2000). Is otolith strontium a useful scalar of life cycles in estuarine fishes? *Fisheries Research* **46**, 359–371. doi:10.1016/S0165-7836(00)00159-4
- Sussmilch, F. G. S. (1914). 'An Introduction to the Geology of New South Wales.' (Angus & Robertson: Sydney.)
- Thomson, J. M. (1996). Family Mugilidae: grey mullets. In 'Freshwater Fishes of South-eastern Australia'. (Ed. R. M. McDowall.) pp. 191–197. (Reed: Sydney.)
- West, R. J., and Walford, T. R. (2000). Estuarine fishes in two large eastern Australian coastal rivers – does prawn trawling influence fish community structure? *Fisheries Management and Ecology* **7**, 523–536. doi:10.1046/J.1365-2400.2000.00222.X

Manuscript received 2 September 2008, accepted 1 March 2009